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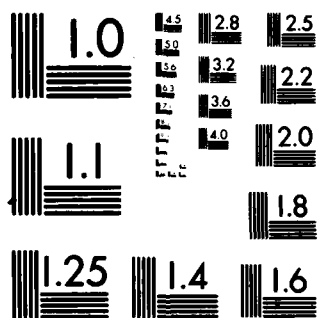
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Technical Document 391

## UNDERWATER SOUND MATHEMATICAL MODEL

E.R. Aughinbaugh

21 October 1980

Final Report for Period October 1979 - September 1980

Prepared for  
Naval Sea Systems Command  
Code 63C1  
Washington DC 20360

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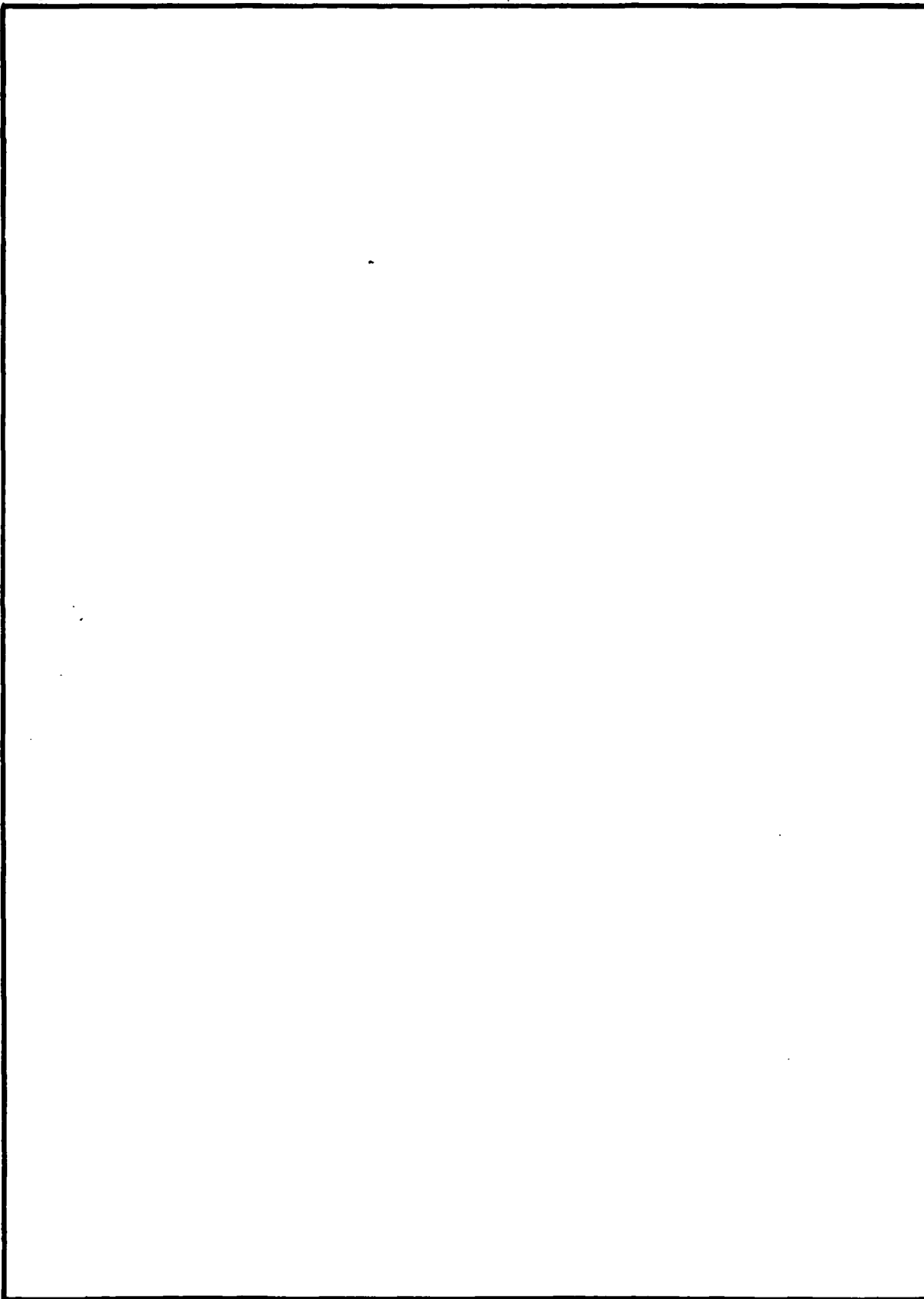
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## 1.0 INTRODUCTION

### 1.1 PURPOSE

This document describes a general ray theory mathematical model of beam formation and underwater sound propagation over short to moderate ranges. Principally, the model was designed as an analytical tool to support in-water performance measurements of typical Naval cylindrical and spherical transducers. However, the performance of linear, planar, and most other array configurations may also be studied. The term "predicted performance," as used here, specifically relates to the sound pressure fields in the near, far, and transition-zone regions of the arrays. The model provides for the treatment of reflective path conditions such as those that exist when signals arrive by surface-reflective, bottom-reflective, and direct paths.

A typical example of the model's utility would be to provide an analysis of a relatively large sonar transducer operating at a low frequency near the surface, where the receiving element (perhaps a test transducer) is in the near field. From this analysis, a test facility, test equipment, and test procedures may be defined and subsequent test data properly interpreted.

### 1.2 BACKGROUND

An evaluation of a sonar's performance may commonly be conducted through source-level measurements of the transmitter and receiving sensitivity measurements of the receiver. In addition, measurements of the system's beam patterns provides main lobe widths and side lobe heights and their bearing locations. These characteristics, measured in the field, are a function of the transducer's design dimensions, element arrangements, phasing, and shading specifications. The beam-pattern characteristics are a function of distance from the transducer. Close to the transducer, beam patterns will change significantly as a function of distance because of constructive and destructive interferences from individual element contributions. At locations far removed from the transducer, beam-pattern shapes become constant. The area of transition from near-field conditions to far-field conditions may be described for a cylindrical array as approximately  $d^2/\lambda$ , where  $d$  is the diameter of the transducer array and  $\lambda$  is the transmission wavelength.

Acoustic behavior in the transition zone is of particular interest to the Navy since most shipboard external measurements are made with a transducer suspended from a 50-foot-long boom extended over the bow. It is necessary to translate these measurements from the transition zone into corresponding values which would be representative of the far field condition to compare them with system specifications, etc. The mathematical model proposed in this document is capable of defining a beam pattern in the far field from measurements which are collected in the near field or transition zone.

The Sensor Accuracy Check Site (SACS), located at the Long Beach Naval Support Activity, measures shipboard sonar systems' performance at a distance of 120 feet through 310° of azimuth. These measurements, at 120 feet, are obtained in the far field of some systems. For others, the measurements are obtained in the transition zone because of facility size constraints. In either case, it is important to relate the SACS measurements to the shipboard 50-foot boom measurements and also to relate all values to the far-field condition.

A distorted beam pattern may result when both a direct and reflected signal from an acoustic source are received simultaneously at a test receiver. The reflection plane is commonly that of the water surface. This phenomenon, called the Lloyd's mirror effect, is especially prevalent when a sonar of relatively large size is operating at a low frequency

close to the surface and over a short distance. At large distances, the reflected signals decay or dissipate and the true performance of the sonar may be observed. Again, since measurements cannot always be obtained far away enough to avoid the reflected path, it then becomes important to quantify the effects of the reflected signal in the near-field test environment. The acoustic math model enables the prediction of the reflected path contributions. From these predictions, the near-field measurements may be compensated for to eliminate the reflected-path contributions.

Orientation of the ship and the sonar transducer is important at the SACS facility during data acquisition, since data are taken at many locations about the ship. A 1° port list on the ship, for example, could affect the relative magnitude of data taken on the port or starboard side of the ship since the test transducer is normally kept at constant depth and will be at different points in the vertical beam. Since the vertical beam is influenced by the Lloyd's mirror effect, data obtained under such conditions may be misleading. The magnitude of vertical beam distortions will vary greatly from one sonar design to another. The model will provide a better understanding of these phenomena.

The application of the model is also intended to aid the SACS facility in analyzing sonar operating deficiencies. It is common to discover sonar systems functioning with some transmitter channels inoperative or at reduced power, or to find staves inoperative or miswired. The relative effects of these deficiencies on in-water measurements are not well understood. Test plans have not been optimized to acquire beam pattern data at locations and over bearing sectors, as well as in transmission modes that would best increase the chances of detecting these deficiencies. Furthermore, adequate processes have not been available to analyze the data and thus separate, for example, phasing problems from dead staff problems. This and the other applications described above are the prime motivations for development of the acoustic math model.

## 2.0 GENERAL APPROACH TO THE MATH MODEL

The math model accounts for the propagation of direct and reflected sound paths from each element of the sonar transducer array to each element of the receiver hydrophone. Thus a multitude of propagation paths are summed to compute the ship's transmitter performance as seen at a single location of the receiver. The model will repeat computations of the transmitter performance as the receiver is moved in azimuth, range, or depth relative to the transmitter. To achieve this end, each contributing element of the source transducer and the receiving transducer must be defined and their contribution to the summation described. The element is defined by its physical dimensions and shape. Its contribution is characterized by its individual beam shape, phasing, and shading.

The characteristic far-field cardioid beam shape of the elements is programmed into the model. The cardioid is assumed to be identical for all elements of the same design. The cardioid is derived from the equation:

$$C = \frac{\sin(KL \sin \phi)}{KL \sin \phi} \times \left(1 + \frac{\cos \phi}{2}\right)^2$$

where K, L are defined in such a manner as to fit an actual measured beam pattern of the element of interest. The element spacing, phasing, and shading parameters and the transducer size are entered into the model so that element-to-element, geometric, and relative

strength relationships may be established. Initially, a generalized planar, general cylindrical, and specific Navy cylindrical arrays will be available to the user. Preprogrammed spherical arrays are planned for a later date.

The orientation of the transducer array (ie, yaw, pitch, roll) is defined by the user. The user also must define the depth of both the transducer array and the receiver, the sound velocity, and the frequency of the transmission. Two reflection planes (surface and bottom) may be accommodated in the model. The planes may have reflection coefficients from -1 to +1. A coefficient of -1 represents a 100% reflection with 180° of phase reversal. A coefficient of +0.5 represents an amplitude reflection of 50% with no phase reversal.

## 2.1 MATHEMATICAL DESCRIPTORS

Since the fundamental units in the model are the individual elements making up both the source and receive transducers, their contribution to the overall transducer must be formulated so that the total effects may be calculated. The math model uses an efficient and easily understood mathematical treatment of this process. Each contribution may be described as having a magnitude and phase within a particular spatial region. Basically then, each contribution may be defined as a vector. The spatial region is described by a particular coordinate system.

The math model uses this concept to operate upon the contributions from each element. Since each contributor may be most easily defined in a coordinate system unique to its physical arrangement, a common spatial region is required before a mathematical treatment such as the required summation may be applied. For example, the source transducer must be referred to the same coordinate system as the receiving transducer. This is most readily implemented through the use of vector notation, as well as translation and rotation of coordinate systems. The math model applies these processes by matrix manipulation to provide the required analysis.

## 3.0 MATH MODEL COORDINATE SYSTEMS

NOSC TD 272 proposed a similar mathematical model based on derivations using trigonometric relationships and complex notation.<sup>1</sup> As stated previously, the model in this paper is derived by use of vector notation. Consider the direct path transmission from the  $m^{\text{th}}$  element of the ship's sonar, array to the  $n^{\text{th}}$  element of the receiver array, as shown in figure 3-1. Since each element is characterized by a directional cardioid, knowledge of the relative orientation of the two elements is required to determine the transmit/receive interaction. Five separate Cartesian coordinate systems are used to define geometrical relationships between the various elements of the sonar array and the receiver array. They are as follows:

- a. Site coordinate system
- b. Ship's transducer coordinate system
- c. Ship's transducer element coordinate system
- d. Site transducer coordinate system
- e. Site transducer element coordinate system.

---

<sup>1</sup>NOSC Technical Document 272, Underwater Sound Mathematical Model, by R. Bell, 15 August 1979.

These five coordinate systems will each be defined in terms which are compatible with the right-hand rule. If one imagines the thumb of the right hand extended in the direction of the positive x-axis, then the index finger will point toward the positive y-axis and the second finger will point toward the positive z-axis.

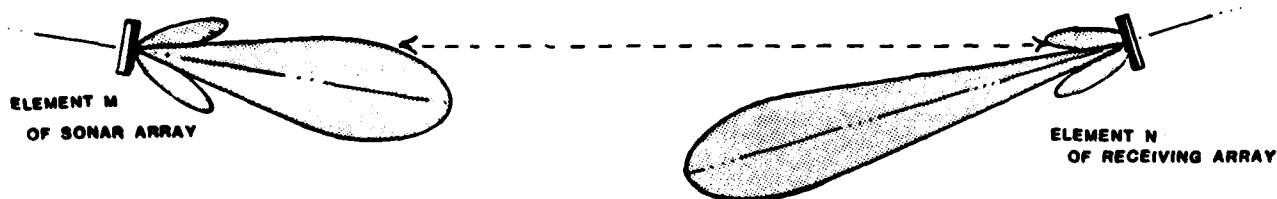


Figure 3-1. Transmit/receive relationship.

### 3.1 SITE COORDINATE SYSTEM

The SACS facility, as mentioned in section 1.2, is a circular pier encompassing  $310^\circ$  of azimuth on a 120-foot radius. The horizontal planar geometric center of the facility at the surface of the water is the origin of the site coordinate system. The origin, therefore, will rise and fall vertically with the tide. The positive x-axis of the site coordinate system is in the direction of the  $000^\circ$  bearing as defined at SACS and as shown in figure 3-2. The

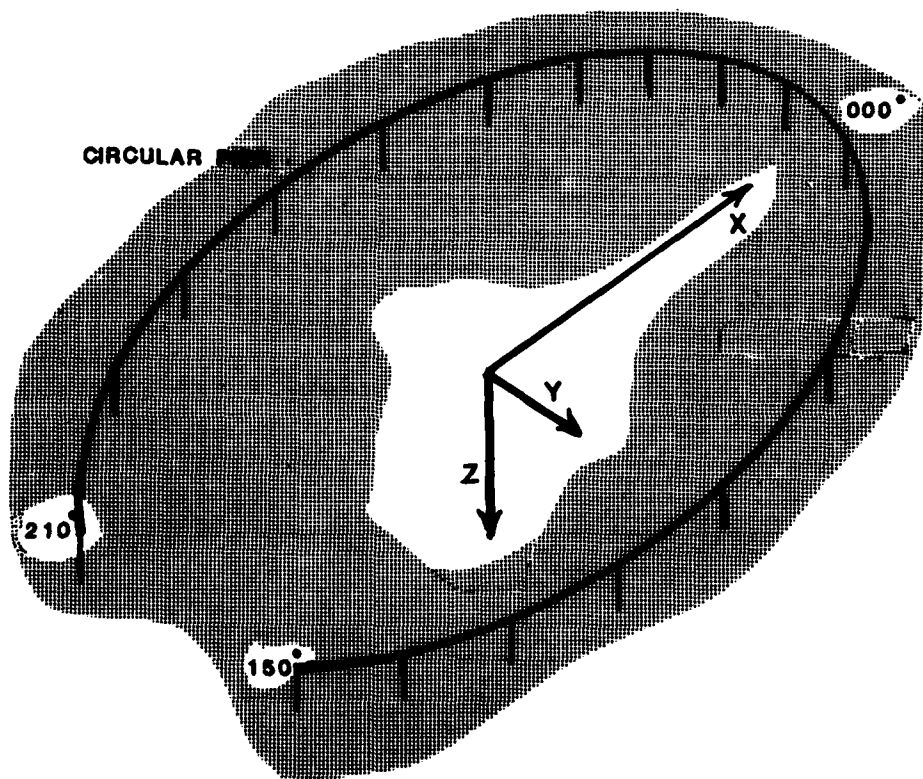


Figure 3-2. SACS site coordinate system.

positive y-axis is at  $90^\circ$  to the x-axis, as shown. The x-y plane is coincident with the surface of the water. The positive z-axis is downward normal to the surface.

### 3.2 SHIP'S TRANSDUCER COORDINATE SYSTEM

The ship's transducer coordinate system is positioned in the vicinity of the site z-axis at some depth. The origin of the ship's transducer coordinate system is defined as the geometric center of the transducer. A planar array will have the x-axis extend from the origin, normal to the planar array, and in the direction of transmission. The y- and z-axes will lie in the plane of the transducer with the z-axis oriented downward.

For a cylindrical array, the x-axis will extend from the origin at the geometric center toward the direction of the designed  $000^\circ$  relative bearing. The designed  $000^\circ$  bearing may pass through stave #1 or it may pass between stave #1 and the last numbered stave, as shown in figure 3-3, when the staves are counted in a clockwise direction. This must be determined for the transducer of interest. The z-axis will be oriented downward, coincident

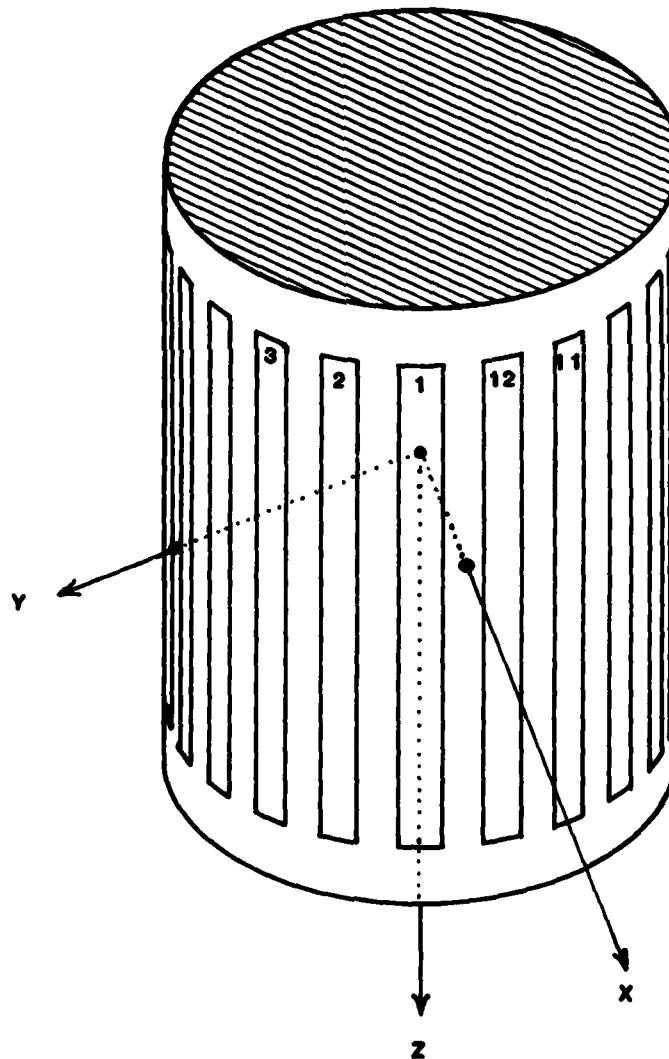


Figure 3-3. Cylindrical array coordinate system.

with the axis of the cylinder. The y-axis will be normal to the x-z plane in compliance with the right-hand rule. All axes of the cylindrical transducer are generally assumed to be coincident with the ship's roll, pitch, and yaw axes. The x-axis is parallel to the ship's centerline. The y-axis is positive in the starboard direction, and the z-axis is positive downward through the keel.

### 3.3 SHIP'S TRANSDUCER ELEMENT COORDINATE SYSTEM

The model approximates each transducer element as being composed of a lightweight, two-dimensional face. Usually, a radiation inhibitor is applied to all exterior portions of the transducer with the exception of the face. The maximum response axis is assumed to be perpendicular to the plane of the transducer face.

The origin of the ship's transducer element coordinate system is located at the center of the two-dimensional radiating face. For a rectangular or square radiating face, the center is defined by the intersection of the diagonals. For a circular face, of course, the origin lies at the center of the circle. Figure 3-4 shows that the positive x-axis is normal to the face of the element and therefore is parallel with the maximum response axis. The positive y- and z-axes lie in the element face, where the z-axis is positive down.

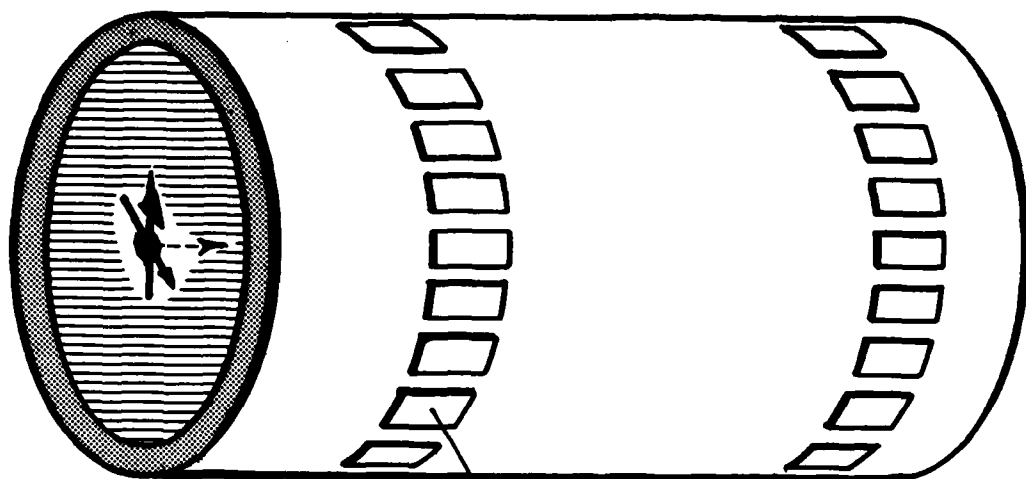
### 3.4 SITE TRANSDUCER COORDINATE SYSTEM

The site transducer will normally be defined as a line hydrophone which is constructed from a series of cylindrical elements 1 inch in diameter by 1 inch in length. The number of elements will determine the physical length of the transducer. This and the electrical wiring of the elements (ie, series or parallel) will determine the beam pattern of the transducer. Three lengths (element configurations) are available.

The site transducer is physically located at the perimeter of the SACS facility; however, for purposes of the math model the site transducer may be positioned at any desired distance. The origin of the site transducer coordinate system is the geometric center of the transducer configuration selected. The positive z-axis will be coincident with the principal axis of the transducer and will point downward. The z-axis of the site transducer will be parallel to the z-axis of the site coordinate system defined in section 3.1. The positive x-axis of the site transducer coordinate system points toward the z-axis of the site coordinate system and is normal to that z-axis.

### 3.5 SITE TRANSDUCER ELEMENT COORDINATE SYSTEM

The origin of each element coordinate system lies at the geometric center of the element cylinder. The positive z-axis is downward along the geometric axis of the cylinder. The positive x-axis points toward the z-axis of the site coordinate system and is normal to it. The y-axis, again, complies with the right-hand rule.



CYLINDRICAL TRANSDUCER  
COMPOSED OF  
RECTANGULAR ELEMENTS

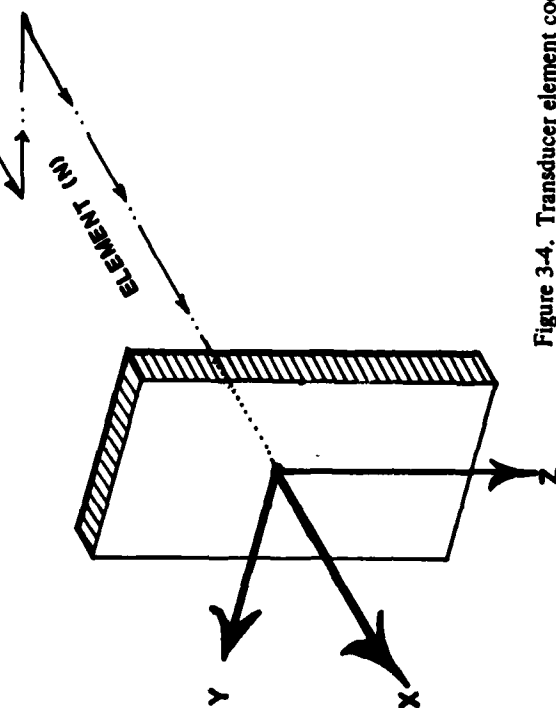


Figure 3-4. Transducer element coordinate system.

## 4.0 VECTORS – TRANSLATION AND ROTATION

The solution required to define the various operating parameters (ie, beam patterns, levels, etc) requires manipulation of the parameters from satellite coordinate systems to a common space coordinate system. Each parameter defined here may be referenced from elementary physics as having a magnitude and direction, which is the classic definition of a vector. The manipulation of these vectors is achieved in the math model by scaling, coordinate translation, and coordinate rotation. Since scaling and translation are trivial manipulations, only the rotation manipulation is discussed.

### 4.1 AXIS PRIORITY

Coordinate rotation from one three-dimensional coordinate system to a second three-dimensional coordinate system involves the consideration of three degrees of freedom. For example, rotation between two coordinate systems on a ship may occur only in the x-y plane (yaw) or only in the x-z plane (pitch) or only in the y-z plane (roll). In reality, the rotation will normally occur in all three planes simultaneously and, therefore, a rotation of a vector in one plane will influence the rotation in the second plane, which will in turn influence the rotation in the third plane. The establishment of an axis rotation priority, therefore, becomes important. The critical factor is that a single priority must be declared and that priority must be used throughout the problem. It should be noted that the order of priority is not critical. Even so, an effort was made to select an axis rotation priority that is compatible with most Naval design criteria. A Navy-wide priority has not been established. However, the ship's gyrocompass is perhaps the best guide to consider. Gyrocompass installations offer two possible alternatives, as shown in figure 4-1.

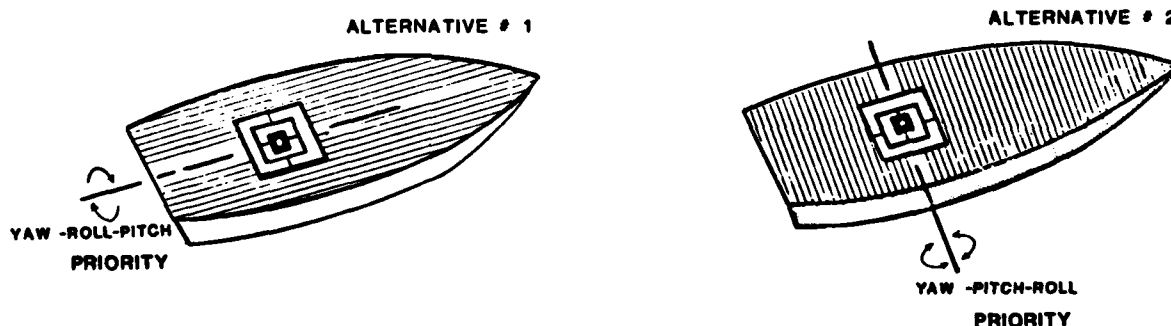


Figure 4-1. Rotational priority.

Gyrocompass gimbals should always be assessed from the inside out. In both alternatives, the azimuth or yaw is measured on the constantly horizontal face of the gyrocompass and is therefore given the highest priority. It will not be corrupted by either roll or pitch motion. Alternative #1 shows the roll axis as the next gimbal and the pitch axis as the outer gimbal, thus defining them as priorities 2 and 3, respectively. In other words, pitch motion will be corrupted by roll motion but not vice versa. Alternative #2 has the reverse gimbal configuration. This is the configuration of the Mark 19 gyrocompass and, therefore, is the priority selected for this document.

Figures 4-2a, 4-2b, and 4-2c show the coordinate rotation matrices<sup>2</sup> for successive rotation about each of the axes in order of priority. The sign convention is: yaw, positive to starboard; pitch, positive up; and roll, positive starboard side down.

For example, in figure 4-2a, a vector which was defined in the x, y, z coordinate system as

$$\vec{V} = x\vec{i} + y\vec{j} + z\vec{k}$$

where  $\vec{i}$ ,  $\vec{j}$ ,  $\vec{k}$  are unit vectors, may be redefined in the  $x'$ ,  $y'$ ,  $z'$  coordinate system as

$$\vec{V} = x'\vec{i}' + y'\vec{j}' + z'\vec{k}'$$

$$\begin{aligned} \text{where } x' &= x\cos\theta + y\sin\theta \\ y' &= -x\sin\theta + y\cos\theta \\ z' &= z. \end{aligned}$$

With the vector now defined in the primed coordinate system, one may proceed to the pitch axis rotation, figure 4-2b, and redefine the vector in the double-primed coordinate system. Finally, the process is repeated for the roll axis rotation.

---

<sup>2</sup>See Goldstein, Herbert, Classical Mechanics, Addison-Wesley Publishing Co., Inc., 1950, p 97.

Θ - YAW

	X	Y	Z
X'	COS Θ	SIN Θ	0
Y'	-SIN Θ	COS Θ	0
Z'	0	0	1

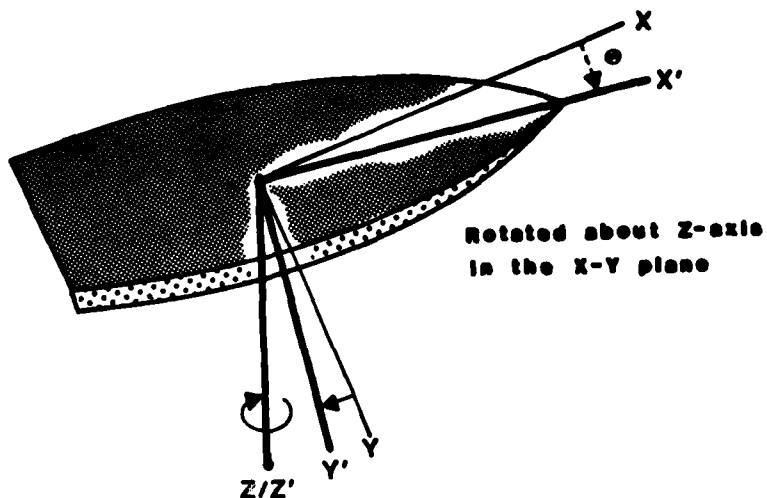


Figure 4-2a

Φ - PITCH

	X'	Y'	Z'
X''	COS Φ	0	-SIN Φ
Y''	0	1	0
Z''	SIN Φ	0	COS Φ

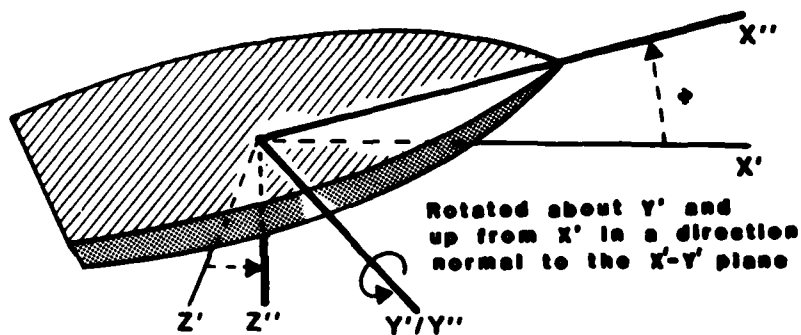


Figure 4-2b

Ψ - ROLL

	X''	Y''	Z''
X'''	1	0	0
Y'''	0	COS Ψ	SIN Ψ
Z'''	0	-SIN Ψ	COS Ψ

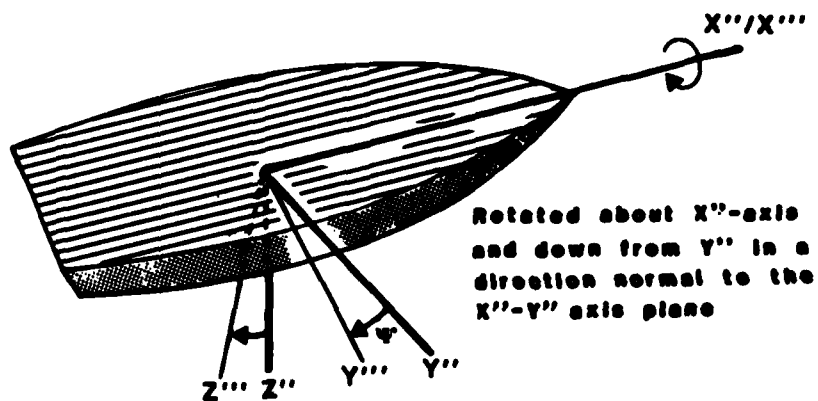


Figure 4-2c

Figure 4-2. Coordinate priority.

## 5.0 DEFINITION AND VECTOR NOTATION

The number of variables that must be used to compute the solutions described in section 2.0 dictates an easily understood characterization of those variables as they are used in the formulation. To this end, a multicharacter notation similar to FORTRAN variable names has been used for vector and matrix quantities. Vectors are indicated by a single arrow,  $\vec{XT}$  and matrices by a double arrow,  $\overleftrightarrow{ASM}$ . The notation  $\vec{XS}(m)$  means the vector associated with the  $m^{\text{th}}$  transducer element. Names associated with ship's transducer contain the letter S; those related to the site transducer contain the letter T.

Section 3.0 described the generalized coordinate systems used in the math model. These descriptions are expanded in the following paragraphs to show the nomenclature used. Figure 5-1 depicts their relationships.

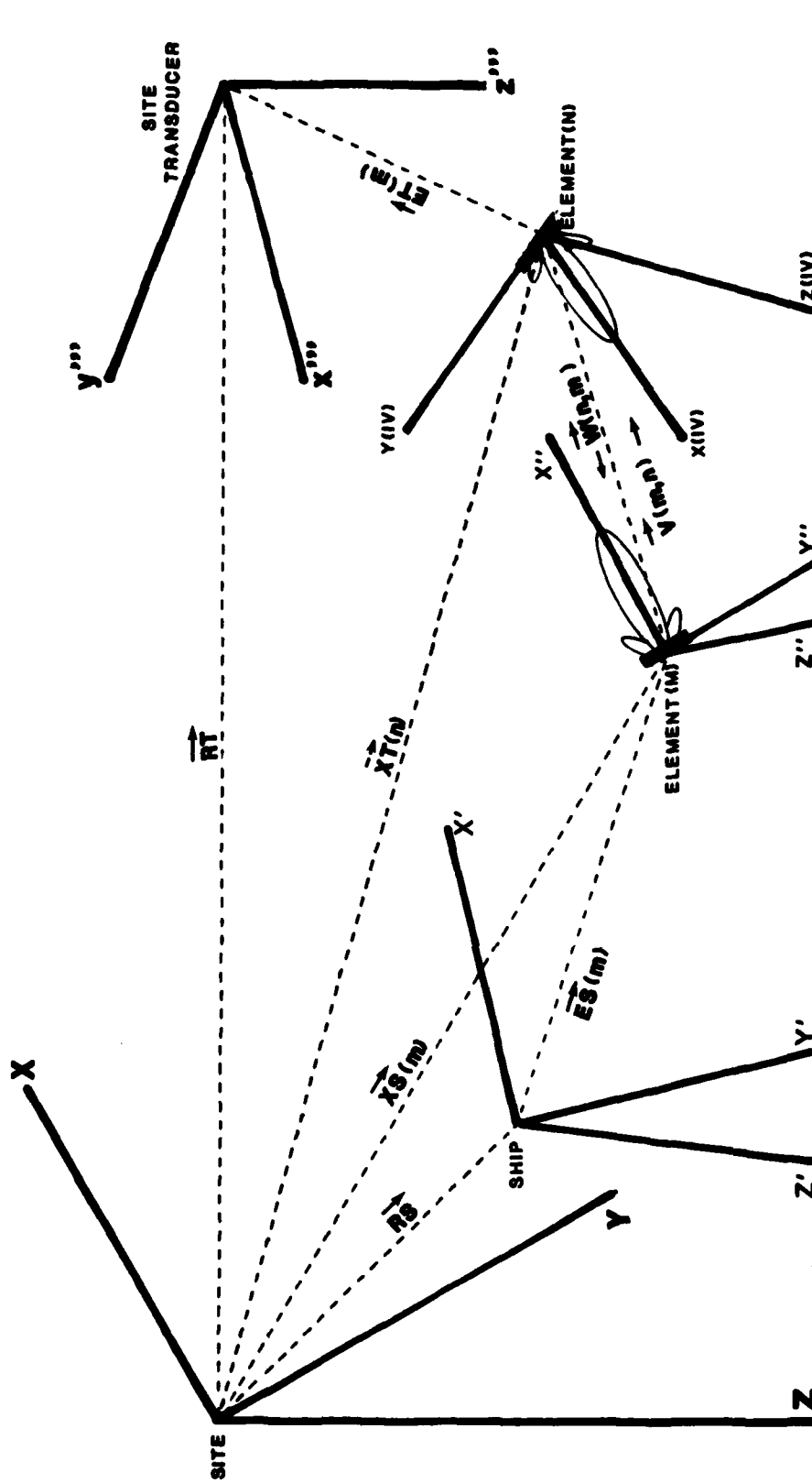
### 5.1 LOCATION OF THE $m^{\text{th}}$ TRANSDUCER ELEMENT IN THE SITE COORDINATE SYSTEM

The location of a transducer element in the ship's coordinate system is defined by the vector  $\vec{ES}(m)$ , where  $\vec{ES}(m)$  is drawn from the center of the ship's coordinate system to the center of the element  $m$  coordinate system.

Since the ship's coordinate system is most probably not coincident with the site coordinate system because of alignment, roll, pitch, and yaw of the ship, commonality of coordinates is still not achieved. To define  $\vec{ES}(m)$  in site coordinates, a vector  $\vec{RS}$  is defined and shown pictorially in figure 5-1.  $\vec{RS}$  is the vector drawn from the center of the site to the geometric center of the ship's transducer. Thus  $\vec{RS}$  is the location of the origin of the ship's coordinate system in site coordinates.

$\vec{ES}(m)$  must be rotated into the site coordinate system. The rotation matrix  $\overleftrightarrow{ASM}$  is used for rotation of the ship's coordinate system into the site coordinate system by the relationship,  $\overleftrightarrow{ASM} \cdot \vec{ES}(m)$ . One other computation defines the vector,  $\vec{XS}(m)$ , which is the location of the  $m^{\text{th}}$  transducer element in site coordinates. From figure 5-1, it can be seen that simple vector addition will define  $\vec{XS}(m)$  by the relationship

$$\vec{XS}(m) = \vec{RS} + \overleftrightarrow{ASM} \cdot \vec{ES}(m).$$



$\vec{ASM}$  = Rotation matrix from ship to site  
 $\vec{BSM}_{(m)}$  = Rotation matrix from element (m) to ship  
 $\vec{PRS}$  = Inverse rotation matrix from site to element (m)  
 $\vec{XS}_{(m)} = RS + ASM \cdot ES_{(m)}$   
 $\vec{ATM}$  = Rotation matrix from transducer to site  
 $\vec{BTM}_{(n)}$  = Rotation matrix from element (n) to transducer  
 $\vec{PRT}_{(n)}$  = Inverse rotation from site to element (n)  
 $\vec{XT}_{(n)} = RT + ATM \cdot ET_{(n)}$

Figure 5-1. Coordinate and vector definition.

## 5.2 BEAM PATTERN DEFINITION IN SITE COORDINATES

BEAMS ( $\vec{V}''$ ) is defined as a beam pattern of a ship's transducer element where  $\vec{V}''$  is a vector in element coordinates. Therefore, BEAMS ( $\vec{V}_m''$ ) represents the relative pressure response of the ship's  $m^{\text{th}}$  transducer element in the direction of  $\vec{V}_m''$  and  $\vec{V}_m$  is drawn from the center of the  $m^{\text{th}}$  element coordinate system.

The rotation matrix  $\overrightarrow{\text{BSM}}(m)$  is used to rotate the  $m^{\text{th}}$  element coordinates into ship's coordinates by the relationship  $\vec{V}_m' = \overrightarrow{\text{BSM}}(m) \vec{V}_m''$ .

The rotation matrix  $\overrightarrow{\text{PRS}}(m)$  is used to rotate the  $m^{\text{th}}$  element coordinates into site coordinates by the relationship

$$\vec{V}_m = \overrightarrow{\text{PRS}}(m) \vec{V}_m''$$

## 5.3 PARAMETER DEFINITIONS

The following variables will be used:

$\vec{\text{RS}}$	=	Location of origin of ship's coordinate system in site coordinates.
$\overrightarrow{\text{ASM}}$	=	Ship-to-site rotation matrix: if $\vec{V}'$ is a vector expressed in ship's coordinates, then $\vec{V} = \overrightarrow{\text{ASM}} \cdot \vec{V}'$ is the same vector in site coordinates.
$\vec{\text{ES}}(m)$	=	Location of the $m^{\text{th}}$ transducer element in ship's coordinates.
$\overrightarrow{\text{BSM}}(m)$	=	Element-to-ship rotation matrix for the $m^{\text{th}}$ element.
$\vec{\text{XS}}(m)$	=	$\vec{\text{RS}} + \overrightarrow{\text{ASM}} \cdot \vec{\text{ES}}(m)$
	=	Location of $m^{\text{th}}$ transducer element in site coordinates.
$\overrightarrow{\text{PRS}}(m)$	=	$\overrightarrow{\text{ASM}}(m) \cdot \overrightarrow{\text{BSM}}$
	=	Complete element-to-site inverse rotation matrix for element $m$ .
BEAMS ( $\vec{V}''$ )	=	Beam pattern of a ship's transducer element where $\vec{V}''$ is a vector in element coordinates.
BEAMS [ $\vec{V} \cdot \overrightarrow{\text{PRS}}(m)$ ]	=	Beam pattern of $m^{\text{th}}$ element expressed in element coordinates where $\vec{V}$ is a vector in site coordinates.

Similarly, for the site transducer

$\vec{RT}$	=	Location of origin of site transducer coordinate system in site coordinates.
$\overrightarrow{ATM}$	=	Site transducer-to-ship rotation matrix.
$\vec{ET}(n)$	=	Location of $n^{th}$ transducer element in transducer coordinates.
$\overrightarrow{BTM}(n)$	=	Element-to-site transducer rotation matrix for $n^{th}$ element.
$\vec{XT}(n)$	=	$\vec{RT} + \overrightarrow{ATM} \cdot \vec{ET}(n)$ = Location of $n^{th}$ element in site coordinates.
$\overrightarrow{PRT}(n)$	=	$\overrightarrow{ATM}(n) \cdot \overrightarrow{BTM}$ = Complete element-to-site inverse rotation matrix for element $n$ .
$BEAM(\vec{V}'')$	=	Beam pattern of a site transducer element where $\vec{V}''$ is a vector in element coordinates.
$BEAM [\vec{V} \cdot \overrightarrow{PRT}(n)]$	=	Beam pattern of $n^{th}$ element where $\vec{V}$ is a vector in site coordinates.

## 6.0 FORMULATION OF THE PROBLEM

The quantities which are required to compute the received signal intensity are the path length from the  $m^{th}$  element of the ship's transducer to the  $n^{th}$  element of the site transducer, and the path vector at each element expressed in the coordinate system of that element. These quantities must be computed for each pair  $(m,n)$  of elements for the direct path and for each reflected path.

The direct path vector from the  $m^{th}$  element of the ship's transducer pointing toward the  $n^{th}$  element of the site transducer is simply the vector difference of the locations of the two transducer elements expressed in site coordinates. Thus

$$\vec{V}(m, n) = \vec{XT}(n) - \vec{XS}(m).$$

The reflected path may be obtained geometrically by moving the source from its position below the reflecting plane to one an equal distance above it. In vector notation, the reflected path is then given by

$$\vec{V}'(m, n) = \vec{XT}(n) - \vec{XS}(m) - 2 [\vec{XT}(n) - \vec{RR}] \cdot \hat{u} \hat{u}$$

where  $\hat{u}$  is a unit vector normal to the reflecting plane in the site system, and  $\vec{RR}$  is any vector to a point on the reflection surface.

Similarly, for the vector path from the  $n^{\text{th}}$  site element to the  $m^{\text{th}}$  ship element,

$$\vec{W}(n, m) = \vec{XS}(m) - \vec{XT}(n)$$

and

$$\vec{W}'(n, m) = \vec{XS}(m) - \vec{XT}(n) - 2 [\vec{XS}(m) - \vec{RR}] \cdot \hat{u} \hat{u}.$$

The magnitudes of the vectors are obviously the same. That is,

$$\sqrt{\vec{V} \cdot \vec{V}} = \sqrt{\vec{W} \cdot \vec{W}}$$

and

$$\sqrt{\vec{V}' \cdot \vec{V}'} = \sqrt{\vec{W}' \cdot \vec{W}'}.$$

The directions, however, are different. The directions as seen at the ship transducer and at the site transducer are necessary for the evaluation of the element beam patterns.

The acoustic part of the problem may be stated quite simply as long as we may assume that the distance between the ship's transducer and the site transducer is great enough that far-field conditions hold for the elements of each transducer. This criterion is more than adequately satisfied for all practical sonars.

A second criterion is that the amplitude and phase shading of the transducer elements be accurately known. A discussion of the problems of element interaction and velocity control is beyond the scope of this paper. Similarly, effects of domes, baffles, and reflectors are ignored, except as they influence the individual element patterns.

These assumptions make it unnecessary to deal with acoustic waves as such. We may instead simply speak of the propagation from the  $m^{\text{th}}$  element of the ship's transducer to the  $n^{\text{th}}$  element of the site transducer in terms of a time (phase) delay and of spherical spreading, depending only on the distance. The amplitudes are also modified by the element pattern functions which have as their arguments the ray arrival angles.

Using complex notation for the signals, we may write the direct-path steady-state transfer function as follows:

$$H(m, n, \omega, c) = \exp \left[ \frac{i\omega}{c} R(m, n) \right] \frac{S(m) T(n)}{R(m, n)} \times$$

$$\text{BEAMS} [\vec{PRS}(m) \cdot \vec{V}(m, n)] \times$$

$$\text{BEAMT} [\vec{PRT}(n) \cdot \vec{W}(n, m)],$$

where  $R^2(m, n) = V(m, n) \cdot V(m, n)$  and  $S(m)$  and  $T(n)$  are the complex shading coefficients of the ship and site transducer elements, respectively;  $\omega$  is the frequency in radians/second; and  $c$  is the speed of sound in the same units as the linear dimensions.

Similarly, for the reflected path, we may write:

$$H'(m, n, \omega, c) = \mu \exp \left[ \frac{i\omega}{c} R'(m, n) \right] \frac{S(m) T(n)}{R'(m, n)} \times$$

$$\text{BEAMS} [\overrightarrow{\text{PRS}}(m) \cdot \overrightarrow{V'}(m, n)] \times$$

$$\text{BEAMT} [\overrightarrow{\text{PRT}}(n) \cdot \overrightarrow{W'}(n, m)] ,$$

where  $\mu$  is the reflection coefficient and

$$(R')^2 = \overrightarrow{V'}(m, n) \cdot \overrightarrow{V'}(m, n) .$$

The total steady-state response for any given geometry is given by the sum

$$H_0(\omega, c, \text{geometry}) = \sum_m \sum_n H(m, n, \omega, c) .$$

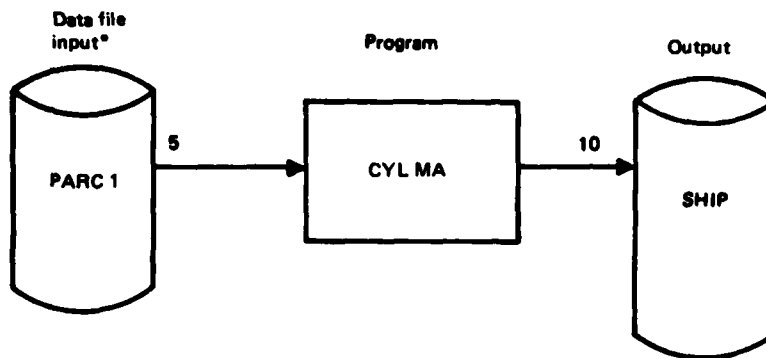
## 7.0 IMPLEMENTATION

The acoustic model is written entirely in FORTRAN, and requires a core memory of 31 000 words. Only minor modifications are necessary to accommodate the program on any medium-size computer supporting FORTRAN and preferably a plotter. Input may be from cards, data files, or direct keyboard entry as the user chooses and the operating system allows. A companion program, CYLGEN, may be used to create a data file describing a cylindrical array.

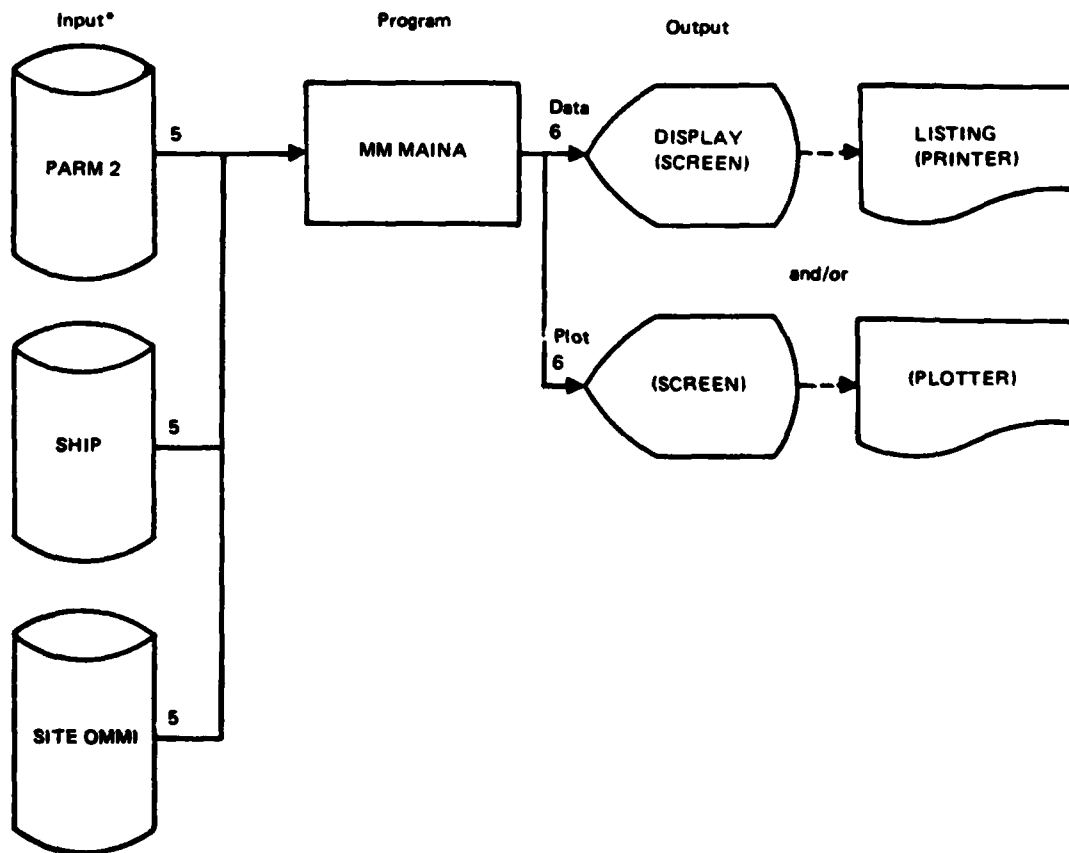
The control statements necessary for operation on the UNIVAC 1100 at NOSC are given in this section. A description of the data inputs and outputs is provided for the user. The model requires three input files for its operation and produces one output file and/or plot. The three input files are the command file, the ship's transducer file, and the site transducer file. The structure is such that the three may be stacked on one input unit.

The command file contains environmental information and experimental conditions such as sound velocity, attenuation factor, reflection coefficients, yaw, pitch, roll, frequency, etc. The two transducer files contain x, y, z positions, amplitudes, and time delays for each element in the ship and site transducers. The ship transducer input file to the main program is sufficiently complex that it must be pregenerated by a separate auxiliary program. An auxiliary program has been written for a cylindrical transducer array known as the Cylindrical Array Generator. Data flow for both the Cylindrical Array Generator and the Main Program are shown in figure 7-1.

Auxiliary program = Cylindrical array generator



Main program = Underwater sound math model



\*Input may be accomplished by disc, tape, or card.

Figure 7-1. Program flow diagram.

## 7.1 CONTROL STATEMENTS

The control statements listed in table 7-1 were extracted from the NOSC Scoop manual.<sup>3</sup> An explanation of the statements and a much more extensive list of statements may be obtained from that manual. The statements in table 7-1 are arranged in the order necessary to execute the cylindrical array generator and the underwater sound math model programs. Statements are also shown for program updating and file printouts.

### Execution of Cylindrical Array Generator Program

```
@USE 10.,SHIP.  
@XQT CYL.MA  
@ADD PARC.1  
to examine:  
@MED,Q SHIP.  
:P *                               or: P n  
                                   : E
```

To terminate present execution,  
@@X (during output, press "break" key).

### Execution of Underwater Sound Math Model Program

```
@SUSPEND  
@XQT MM.MAINA  
@ADD PARM.2  
@ADD SHIP.  
@ADD SITE.OMNI  
@RESUME,E                          for examination  
or @RESUME,P TPR                   for print  
@RESUME,D                          for deletion  
@N*LIB.TEK                         plot on screen.  
(Press 3 times "return" key or enter scale factor = 0.75.)
```

If necessary,  
@DELETE PLOTS.

### Program Updating

```
@MED,Q MM.MAIN                     (Q stands for ASCII data)  
... (updating)  
@FTN,N MM.MAIN,.MAINR              (FTN for ASCII FORTRAN)  
@PACK MM.  
@MAP , MM.MAINA @MAP ,MM.MAINA  
: IN MM.  
: LIB N*ADISSPLA.  
: LIB N*FTNLIB.  
: END
```

Table 7-1. Control statements.

<sup>3</sup>See: System Control Language and Operations and User Oriented Procedures (for use on NOSC 1100/1108 Univac computers only), prepared under NOSC contract N00123-74-C-0312.

## File Printouts

### Printout program file

@SUSPEND  
@PRT,S MM.MAIN  
@RESUME,P TRP

Or for the entire file:  
@N\*LIB.GEN,KM MM.

### Printout data file

@SUSPEND  
@MED,Q SHIP.  
: P \*  
@RESUME,P TRP

Or @MED,Q 10.

Table 7-1. Control statements. (Continued)

## 7.2 CYLINDRICAL ARRAY GENERATOR

The cylindrical array generator program diagrammed in figure 7-1 requires a parameter input designated PARC. The input parameters and their definitions are shown in table 7-2. Upon execution of the program, an output file will be generated. This output file is shown in table 7-3. The file becomes the ship's transducer file and will be used as the input to the main program. This file will be discussed again in section 7.3.1.2.

### a) Data formats and sequence

LTITLE		15A4
NLAYER,NSTAVE,NACTIV		3I10
CENTER,RADIUS,DELZ,SOUNDS		4F20.0
LTYPE,PARAMS(3) = width, height, exponent		A6,3F20.0
IVSHAD		I10
VSHAD(n <sub>layer</sub> ) = 1,2,3,4,	(if IVSHAD=1)	4F20.0
5,6,7,8		4F20.0
IASHAD		I10
ASHAD(n <sub>activ staves</sub> ) = 1,2,3,4,	(if IASHAD=1)	4F20.0
5,6,7,8		4F20.0
IPSHAD		I10
PSHAD(n <sub>active staves</sub> ) = 1,2,3,4	(if IPSHAD=1)	4F20.0
5,6,7,8		4F20.0

### b) For example, file element name PARC.1

SQS-23, SDT  
9, 48, 16  
0., 45.75, 6., 60000.  
RECTB, 5.75, 5.75, 2.  
0  
1  
0.59, 0.69, 0.77, 0.85  
0.92, 0.96, 0.99, 1.00  
1.00, 0.99, 0.96, 0.92  
0.85, 0.77, 0.69, 0.59  
0

Table 7-2. Input data file (PARC) for cylindrical array generator.

c) Explanation of the parameters

LTITLE	= Title
NLAYER	= Number of layers of elements (right-bounded)
NSTAVE	= Number of staves in full circle
NACTIV	= Number of staves in active sector
CENTER	= Relative bearing of sector center in degrees
RADIUS	= Radius of cylinder
DELZ	= Layer spacing in vertical
SOUNDS	= Speed of sound (transducer design parameter)
LTYPE	= Element type code (left-bounded: OMNI, RECT, CIRC, OMNIB, RECTB, CIRCB)
PARAMS(3)	= Element parameters: width, height, exponent of cardioid function
IVSHAD	= 1 for vertical shading; 0 for uniform
VSHAD	= Vertical amplitude shading
IASHAD	= 1 for azimuthal shading; 0 for uniform
ASHAD	= Azimuthal amplitude shading
IPSHAD	= 1 for azimuthal time shading; 0 for uniform, ie, plane wave
PSHAD	= Azimuthal time shading as addition to plane wave, in seconds.

NOTE: Use a common unit for measures of length and derivations, eg, m, ft, or in. (In the following data file, the inch is used.)

Table 7-2. Input data file (PARC) for cylindrical array generator. (Continued)

a) Data formats and sequence

LTITLE	15A4
NELT,LTYPE,PARAMS(3) = width, height, exponent	15,A6,3G16.6
NSEQ, 1,X,Y,Z	2I5,3G20.6
NSEQ,2,PHI,0.,0.	2I5,3G20.6
NSEQ, 3,AMP,DELAY	2I5,3G20.6
NSEQ, 1, X,Y,Z	2I5,3G20.6
NSEQ, 2, PHI,0.,0.	2I5,3G20.6
NSEQ, 3,AMP,DELAY	2I5,3G20.6

b) For example, file name SHIP.

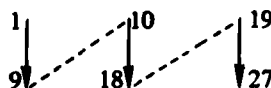
SQS-23,SDT  
 144,RECTB,5.75,5.75,1.  
 1,1,25.42,-38.04,-24.0  
 1,2,-56.25,0.,0.  
 1,3,0.59,-0.3389-003  
 2,1,25.42,-38.04,-18.0  
 2,2,-56.25,0.,0.  
 2,3,0.59,-0.3389-003

Table 7-3. Output data file for cylindrical array generator (ship's transducer file for main program).

c) Explanation of the variables

NELT = NLAYER X NACTIV = total number of active elements

NSEQ = element number, eg,

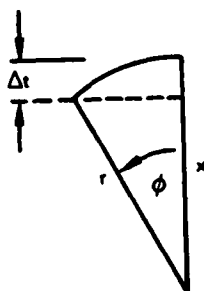


X,Y,Z = coordinates in the ship's transducer coordinate system (origin = center,  
X-axis = ship's heading, Z-axis = downwards)

PHI = polar coordinate in XY-plane in degrees

AMP = total amplitude shading (AMP = ASHAD X VSHAD)

DELAY = time delay in seconds (-sign means transmitting before).



$$\Delta t = \frac{r(1 - \cos \phi)}{c} = \frac{r - X}{c}$$

Table 7-3. Output data file for cylindrical array generator (ship's transducer file for main program). (Continued)

## 7.3 MAIN PROGRAM

### 7.3.1 Input Data Files

The input data files consist of the command file, the ship's transducer file, and the site transducer file. The geometrical position and size of transducer elements, the position of the ship with respect to the site center, the range to the carriage, and the position of any reflecting planes are given in any convenient unit of length. However, it is necessary that all such data be given in the same units of length. It is also necessary that the speed of sound be given in compatible units. Thus, if the positions and sizes are given in feet, the speed of sound must be in feet per second.

**7.3.1.1 COMMAND FILE.** The command file is read from the FORTRAN standard input device. The contents and format of this file are shown in table 7-4. Note that most FORTRAN systems [including the UNIVAC 1100 FORTRAN (ASCII)] require the data in I-formats to be right-justified.

**7.3.1.1.1 Title of Run.** The first record is a 60-character alphanumeric record which will be reproduced verbatim on the printed output and on the plot. It may be anything which suitably identifies the run.

a) Data formats and sequence

Line 1:	ITITLE		18A4
2:	SOUNDS,ATTEN		2F16.0
3:	REFLOS(1),UN(1,1)=x,y,z(normal vector)	reflecting	4F16.0
4:	SURF(1,1)=x,y,z(any surface point)	plane 1	3F16.0
5:	REFLOS(2),UN(1,2)=x,y,z	reflecting	4F16.0
6:	SURF(1,2)=x,y,z	plane 2	3F16.0
7:	RS(3)=x,y,z		3F16.0
8:	YAW,PITCH,ROLL		3F16.0
9:	LUNS		15
10:	RANGE,BEAR,DEPTH,ELEV		4F16.0
11:	LUNT		15
12:	FREQ		F16.0
13:	LNAME,LINLOG,STEP,FINAL,NDEBUG		2A6,2F16.0,A
14:	YPRNG		

b) For example, file element name PARM.2

Line 1:	SQS-23, SDT
2:	60000.,0.
3:	0.,0.,0.,1.
4:	0.,0.,0.
5:	0.,0.,0.,1.
6:	0.,0.,6000.
7:	0.,0.,0.
8:	0.,0.,0.
9:	5
10:	1440.,-90,0.,0.
11:	5
12:	5000.
13:	BEAR,LIN,1.,90.
14:	40.

c) Explanation of the new parameters

ATTEN	=	attenuation	
REFLOS(I)	=	reflection loss (coefficient for reflection plane I)	
UN(I,3)	=	normal vector to reflecting plane I	
SURF(I,3)	=	any surface point (x,y,z,) of the reflecting plane I	
RS(3)	=	ship's transducer center (x,y,z)	
YAW	=	rotation cw about z-axis	} of ship's transducer system
PITCH	=	rotation cw about y'-axis	
ROLL	=	rotation cw about x''-axis	
LUNS	=	unit number for ship's transducer data file	
RANGE	=	site range or radius	
BEAR	=	start of bearing (sector) or carriage bearing	
DEPTH	=	carriage depth (site transducer)	
ELEV	=	carriage "elevation angle"	
LUNT	=	unit number for transducer site data file frequency	
LNAME	=	mode: BEAR, RANGE, DEPTH, ELEV, FREQ	

Table 7-4. Command file.

LINLOG	= LIN for linear mode; LOG for logarithmic mode (eg, frequency, range); POL for polar plot
STEP	= calculation step
FINAL	= end of carriage bearing
NDEBUG	= dump for dump output
YPRNGE	= range for y-axis in plot, usually 40 (ie, -40 dB)

Table 7-4. Command file. (Continued)

**7.3.1.1.2 Environmental Data.** The second record contains basic environment data: the speed of sound and the attenuation of sound per unit distance traveled are specified in this record. Note that both these values involve a unit of length. The unit of length used is arbitrary, but it must be the same for all data items based on length, position, or physical size.

**7.3.1.1.3 Reflecting Planes.** The model has, at present, provision for two reflecting planes. Thus, records 3 and 4 specify the first plane, and records 5 and 6 specify the second plane. A reflecting plane in this model is smooth, of infinite extent, may be placed in any position, and may have any reflection coefficient from +1.0 to -1.0. The reflection coefficient is specified as an amplitude ratio. A value of +1.0 represents a perfectly rigid reflecting surface. A value of -1.0 represents a perfect pressure-release reflecting surface. The surface of still water is, for all practical purposes, a perfect pressure release surface. The bottom reflection coefficient is a function of grazing angle, frequency, and bottom type. A wide range of values is cited in the literature.<sup>4</sup>

The orientation of the plane is specified by the components of a vector which is perpendicular to the plane. For instance, a horizontal plane, such as the surface of the water, is specified by a vertical vector. That is, one whose "z" component is nonzero, and whose "x" and "y" components are zero. Only the ratios of the components are important; the magnitude of the vector is unimportant.

The plane is positioned laterally by specifying the coordinates of any convenient point on the plane with respect to the site center. If the vertical reference is taken to be the surface of the water, the most convenient point for specifying the bottom as a reflecting plane is the point at  $x = 0$ ,  $y = 0$ ,  $z = \text{water depth}$ .

**7.3.1.1.4 Position of the Ship.** The position of the ship's transducer is defined by the  $x$ ,  $y$ , and  $z$  coordinates of the center of the transducer, and the yaw, pitch, and roll angles. For a perfectly aligned ship,  $x = y = 0$ . The  $z$  coordinate is determined by the ship class, sonar type, etc. It is simply the depth of the transducer center.

Angular measurements are defined as in section 4.3. Yaw is measured clockwise in degrees from the "x" axis. This is the normal compass definition. Pitch is measured in degrees, with a positive number being bow up. Roll is measured in degrees with positive being a roll to starboard. The order in which rotations are applied is important. The position of the ship as defined in the SACS MODEL is as follows. Starting with a ship in perfect alignment in the site, it is first yawed about the "z" axis, pitched about the "y" axis, and, finally, rolled about the "x" axis. Similar definitions apply to the elements within a transducer.

<sup>4</sup>See, for instance, Urlick, R. J., *Principles of Underwater Sound*, McGraw-Hill, 1975, p 121-135.

**7.3.1.1.5 Ship's Transducer Data.** The data file containing the ship's transducer specifications will be read from the FORTRAN input unit specified in record 9. If this unit is the same as the standard input unit (unit 5 on the UNIVAC 1100), then the ship's transducer data must immediately follow the last record of the command file.

**7.3.1.1.6 Geometrical Data.** Record 10 contains the geometrical parameters. The range is specified in the chosen units of length. For beam pattern measurements, the site radius is used. Bearing is the site transducer bearing as seen from the ship. It is measured clockwise from the "x" axis. If bearing is to be the independent variable, then the initial value specified here must be algebraically less than the final value. This means that bearings counterclockwise from the "x" axis must be negative (that is, use  $-90^\circ$ , not  $270^\circ$ ).

The depth of the carriage transducer is its "z" coordinate measured from the site origin (usually the surface of the water). The elevation angle is a nonphysical angle used for plotting vertical beam patterns. It is the angle with respect to the horizontal of an imaginary arm carrying the site transducer at one end, and whose other end is at  $x = 0$ ,  $y = 0$ ,  $z =$  site transducer depth. Its value in record 10 should be zero, unless it is used as the independent variable.

**7.3.1.1.7 Site Transducer Data.** The data file containing the site's transducer specifications will be read from the FORTRAN unit specified in record 11. If this unit is the same as the standard input unit (unit 5 on the UNIVAC 1100), then the site transducer data must immediately follow the last record of the control file if the ship data were not read from the standard input. It will directly follow the last record of the ship transducer file if the site unit is the same as the ship unit. The contents of the transducer file are discussed in section 7.3.1.2.

**7.3.1.1.8 Frequency.** The frequency to be used in the calculations is given in record 12 (Hz).

**7.3.1.1.9 Independent Variable Selection.** The independent or loop variable is selected by name in record 13. The legal names are RANGE, BEAR, DEPTH, ELEV, and FREQ. The incrementation modes are selected by name. The legal names are LIN, LOG, and POL. LIN and POL produce a linear incrementation of the selected variable; LOG produces a logarithmic incrementation. The step size is specified in the same units as the selected variable for LIN and POL; it is specified in steps per decade in LOG. In all cases, the final value is specified in the same units as the selected variable.

Note that the POL produces a polar plot, while LIN and LOG produce rectangular plots. POL can only be used with the variables BEAR and ELEV.

There is another alphanumeric field in this record. If it contains the word "DUMP," all of the various vectors and matrices will be dumped for each value of the independent variable.

**7.3.1.1.10 Plot Range.** The last record contains the range of data values to plot. The plots are automatically normalized so that the peak value = 0.0 dB. The dynamic range in dB of the plot is specified by the first field of the last record. (The specification may be either positive or negative. The sign is ignored.) The second and third fields of the last records specify the minimum and maximum values for the abscissa of the plot so that the plot may be forced to a user-defined scale, regardless of the range of the independent

variable. The abscissa limits are specified in the same units as the independent variable. The following characteristics should be noted:

- a. If both the second and third field are blank, the plot limits will be taken from the loop limits of the independent variable.
- b. If either field is specified, the other must be specified also.
- c. The loop limits of the independent variable will be readjusted to prevent calculation of the values outside the plot limits.
- d. The abscissa plot limits are ignored for polar plots.

**7.3.1.2 SHIP TRANSDUCER FILE.** The ship transducer file input may either be obtained from the cylindrical array generator program as mentioned in section 7.2, or may be manually constructed for simple linear and planar arrays. Eventually, other array generator programs will be written to accommodate, for example, spherical arrays. Table 7-5 shows an example of the ship transducer file input.

a) Data formats and sequence

Line 1:	LABLS	15A4
2:	MM,ITYPS,PARS(3) = width, height, exponent)	15,A6,3F16.0
3:	MT,1,T(3) = x,y,z,	2I5,3F20.0
4:	MT,2,T(3) = PHI,0.,0.	2I5,3F20.0
5:	MT,3,T(3) = AMP,DELAY	2I5,3F20.0
6:	MT,1,T(3)	2I5,3F20.0
7:	MT,2,T(3)	2I5,3F20.0
8:	MT,3,T(3)	2I5,3F20.0

(Loop variable = MM)

b) For example, file name SHIP.

```
SQS-23,SDT
144,RECTB,5.75,5.75,2.
1,1,25.42,-38.04,-24.0
1,2,-56.25,0.,0.
1,3,0.59,-0.3389-003
2,1,25.42,-38.04,-18.0
2,2,-56.25,0.,0.
2,3,0.59,-0.3389-003
```

c) Explanation of the new variables:

LABS	= LTITLE
MM	= NELT
ITYPS	= LTYPE
PARS(3)	= PARAM(3)
MT	= NSEQ
T(3) <sub>1</sub>	= ES(3 = x,y,z)
T(3) <sub>2</sub>	= YAW, PITCH, ROLL = THETA, PHI, PSI
	(angles of elements for rotation matrix)
T(3) <sub>3</sub>	= SA(M), SP(M) = AMP, DELAY

Table 7-5. Ship transducer file.

**7.3.1.2.1 Transducer File Title.** The first record in a transducer file is a 60-character alphanumeric record which will be reproduced verbatim on the printed output and on the plot. It may be anything which suitably identifies the transducer file.

**7.3.1.2.2 Element Description.** The second record describes the elements used to build the transducer. Note that all elements must be alike. There are presently six types of elements which may be selected by name: OMNI, OMNIB, RECT, RECTB, CIRC, and CIRCB. Type OMNI is a point-omnidirectional element. Type RECT is a rectangular element with a width and height specified by parameters 1 and 2, respectively. Type CIRC is a circular element with a diameter specified by parameter 1. Types ending in "B" are the same as the corresponding types without the "B", except that the element pattern cardioid is multiplied by a power function intended to represent the effects of a baffle. The power to which the cardioid is raised is given by parameter 3.

**7.3.1.2.3 Individual Element Data.** The position, attitude, and drive for each element are specified in groups of three records. The position of the element with respect to the transducer center is given by the x, y, and z coordinates in the first record of the triplet.

The angular position or attitude of the element is specified as its "yaw," "pitch," and "roll" in the second record of the triplet. Element yaw is measured from the ship's head for the ship transducer, and from the (inward) radius vector for the site transducer. Refer to sections 4.3 and 7.3.1.1.4 for a discussion of the order of angular displacements.

The third record of the triplet specifies the amplitude and time delay of the element. These numbers describe the shading and beamforming of the transducer array. Positive numbers imply a delay of the signal; negative, an advance.

Note that the first field of each record contains the element number. (The ordering of the elements is arbitrary, but once numbered, the element description records must be in order.) The second field contains 1, 2, or 3 to identify the card in the triplet. These fields are error-checked. This feature was included to protect against the inadvertent shuffling of a large, hard-to-read data deck, should this input be prepared on cards.

**7.3.1.3 SITE TRANSDUCER FILE.** The site transducer file contains parameters which specify the geometry, critical dimensions, and electrical phasing characteristics of the site transducer or receiver. This information is outlined in table 7-6.

- a) Data format and sequence (the same as ship's transducer!)

LABLT	15A4
NN,ITYPT,PART(3 = width, height, exponent)	I5,A6,3F16.0
MT,1,T(3) = x,y,z	2I5,3F20.0
MT,2,T(3) = $\nu, \phi, \psi$ (yaw, pitch, roll)	2I5,3F20.0
MT,3,T(3) = amplitude, time delay	2I5,3F20.0

- b) For example, file element, name SITE-OMNI

OMNI  
1,OMNI,0.,0.,0.  
1,1. (blank = zeros)  
1,2. (blank = zeros)  
1,3,1., (blank = zeros)

Table 7-6. Site transducer file.

c) Explanation of the new variables

LABLT	= title
NN	= number of elements
ITYPT	= element type code (OMNI, RECT, CIRC, OMNIB, RECTB, CIRCB)
PART(3)	= width, height, exponent for element type

Table 7-6. Site transducer file. (Continued)

### 7.3.2 Output Data Files

The outputs are either a printed data file containing a header record followed by the independent and dependent variables for each point calculated; a plot; or both. (This is a compile time option.)

The primary output of the SACS model is a plot of relative received level in dB versus the selected independent variable. The peak value (corresponding to 0.0 dB) is included in the plot annotation.

In principle, the received level is the product of the source level of one transducer, the receiving sensitivity of the other, the beam-pattern functions of the two transducers, the spherical spreading, and the attenuation for the particular path. Due allowance must be made for the unit of length used, as this is the reference distance for the source level. In practice, one must also consider the effects of being in the near field or the transition region of one or both transducers.

The source level can be defined as

$$SL = 10 \log \left| \sum_{n=1}^N a_n b_n \exp \left[ i\omega(t_n - x_n/e) \right] \right|^2$$

where the  $a_n$  are the amplitude-shaping coefficients, the  $b_n$  are the element beam-pattern functions evaluated for a sound wave traveling along the maximum response axis of the array, the  $t_n$  are the beamformer time delays, and the  $x_n$  are the physical displacements of the elements measured from some convenient reference plane and also measured along the direction of the maximum response axis. The quantity,  $e$ , is the speed of sound.

Since this expression is difficult to evaluate in the general case, one should note that it can be obtained from the program by determining the peak level through the use of a large value for range and a test transducer with one omnidirectional element of unit sensitivity. The source peak is then

$$L_s = (\text{peak level}) + 20 \log (R/r_0)$$

where "peak level" is the peak level printed on the plot,  $R$  is the range, and  $r_0$  is the reference distance for which the source level is desired. Both  $R$  and  $r_0$  must be expressed in the same units. For this procedure to work, the range must satisfy the inequalities

$$5 \times 10^4 \lambda > R \gg f^2/\lambda ,$$

where  $\lambda$  is the wave length, and  $f$  is the maximum dimension of the array. Implicit in this statement is the restriction that

$$f < 223 \lambda .$$

One may reverse the procedure to obtain the receiving sensitivity by using an omnidirectional source of unit strength. The result is that for the purposes of this model, the source level and receiving sensitivity of a transducer are numerically the same.

The units one places on source level and receiving sensitivity are arbitrary; one need only be consistent.

**7.3.2.1 PRINTED OUTPUTS.** The SACS model echoes the data input from the control file on the FORTRAN standard output device (terminal or printer, as specified for the run). The transducer file title, number of elements, element type, and element parameters are also printed for each transducer file. The element position, attitude, shading and time delay are not printed. Each value of the independent variable and the result (as amplitude squared) are then printed. Table 7-7 shows the data parameters and format for a printed output.

Data format and sequence for printout:

ITITLE		15A4
SOUNDS,ATTEN		(G16,6)
REFLOS(J)		G16.6
UN(J,3)	J=1,2	3G16.6
SURF (J,3)		3G16.6
RS(3) = x,y,z		3G16.6
YAW,PITCH,ROLL		(G16,6)
RANGE,BEAR		(G16,6)
DEPTH,ELEV		(G16,6)
FREQ		G16.6
LNAME,LINLOG		AG,A3
STEP		G16.6
FINAL		G16.6
LUNS		G16.6
LABLS		12
MM,ITYPS		15A4
PARS(3)		15,AG
LUNT		3G16.6
LABLT		
NN,ITYPT		
PART(3)		
ITITLE		(12A4)
LNAME,LINLOG		
VARLUP(I),RESULT		2G16.6
VARLUP(I),RESULT		2G16.6

Table 7-7. Output file.

**7.3.2.2 PLOTTER OUTPUTS.** The major output of the model is a plot of relative received levels versus the selected independent variable. The plot is annotated with the run title, the transducer file titles, and the value (in dB) corresponding to 0.0 dB on the plot.

#### **REFERENCES**

1. NOSC Technical Document 272, Underwater Sound Mathematical Model, by R. Bell, 15 August 1979.
2. Goldstein, Herbert, Classical Mechanics, Addison-Wesley Publishing Co., Inc., 1950, p 97.
3. System Control Language and Operations and User Oriented Procedures (for use on NOSC 1100/1108 Univac computers only), prepared under NOSC contract N00123-74-C-0312.
4. Urick, R. J., Principles of Underwater Sound, McGraw-Hill, 1975, p 121-135.